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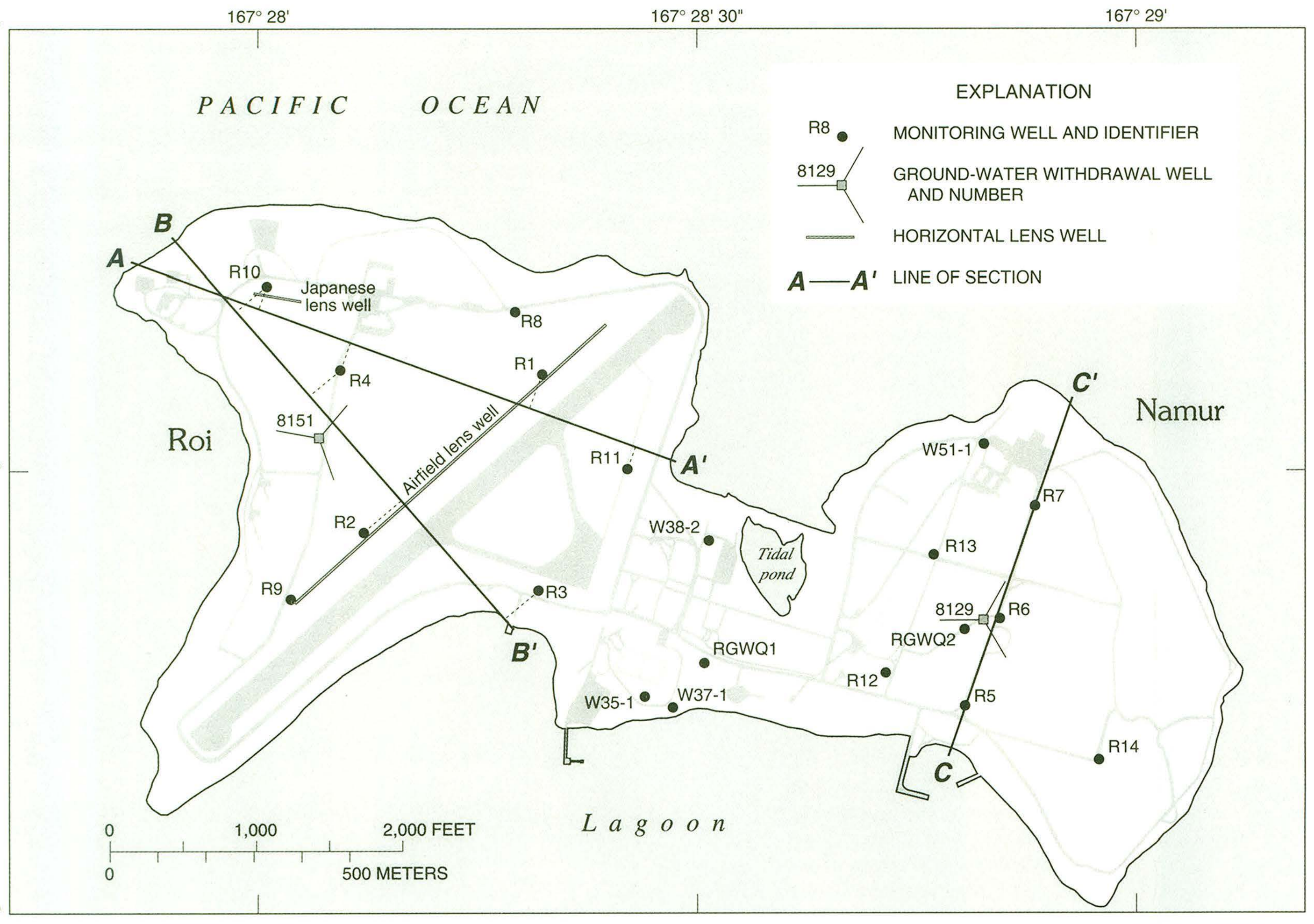

Figure 6. Ground-water withdrawal wells, monitoring wells, and lines of section, Roi-Namur Island.

GROUND-WATER WITHDRAWAL WELLS AND MONITORING WELLS

Horizontal wells are used to skim water from the thin freshwater lens without raising salinity. Monitoring wells enable water sampling and hydrologic measurements at many locations and at various depths on the island.

The principal ground-water withdrawal well on Roi-Namur Island is the airfield lens well, a 3,000-ft long, multi-pump, linear well system, capable of producing 65,000 gal/d. The well consists of a perforated pipe laid in a shallow, horizontal trench (fig. 6 and table 2). The two southernmost sections of the lens wells are not in use because they pump water with chloride concentrations unacceptably high for drinking (Larry Hildebrand, Johnson Controls, Inc., oral commun., 1990). The horizontal well is known on Roi-Namur as a lens well or skimming well, and is referred to more widely as an infiltration gallery. A horizontal well minimizes the salinity of water pumped from a thin lens because:

(1) the well is just beneath the water table as far from the underlying freshwater-saltwater transition zone as practicable; and

(2) the well spreads withdrawal over a long length of the aquifer, resulting in a broad, shallow drawdown trough instead of a deep, localized drawdown cone.

In 1993, the airfield lens well was the only well used for domestic supply. Two other wells developed small quantities of water locally for non-domestic uses such as cooling water, construction water, and landscape irrigation.

A total of 55 monitoring wells clustered at 20 sites have been constructed on Roi-Namur for studies of ground-water supply and contamination. Locations of the monitoring-well sites are shown in figure 6. The wells are grouped below by purpose and construction design.

R-series wells.--This network consists of 49 wells at 14 sites. A typical well site has five 2-in. diameter wells that extend to various depths below the water table and have short (1 to 2 ft) perforated intervals at their bottoms. One site (R1) has a 3-in. diameter well with a 9-ft long screen for aquifer testing. The 49 wells were built in 1990.

The R-series wells are completed to depths of as much as 55 feet below sea level and were the principal hydrologic monitoring network for this study. Water samples from the wells were analyzed to estimate freshwater extent and thickness. Water levels were measured to deduce ground-water flow directions and hydraulic properties of the aquifer.

W- and RGWQ-series wells.--These six wells were constructed in 1990 for an investigation of ground-water contamination. There is one well per contamination site, and the wells are perforated along most of their length, including at the water-table zone so that floating contaminants can be detected.

Table 2. Design of ground-water withdrawal wells, Roi-Namur Island

[Well designs are from Nemeth (1991) and L. Hildebrand, Johnson Controls World Services, Inc., Kwajalein, personal commun., 1990]

Well	Use	Well design
Airfield lens well	Domestic supply	Length: 3,000 ft, A–F are individual sumps
LW 8151	Irrigation (golf course)	Three 300-ft lateral intakes, 120° spacing
LW 8129	Non-potable construction	Three 300-ft lateral intakes, 120° spacing
Japanese lens well	Unused	Unknown

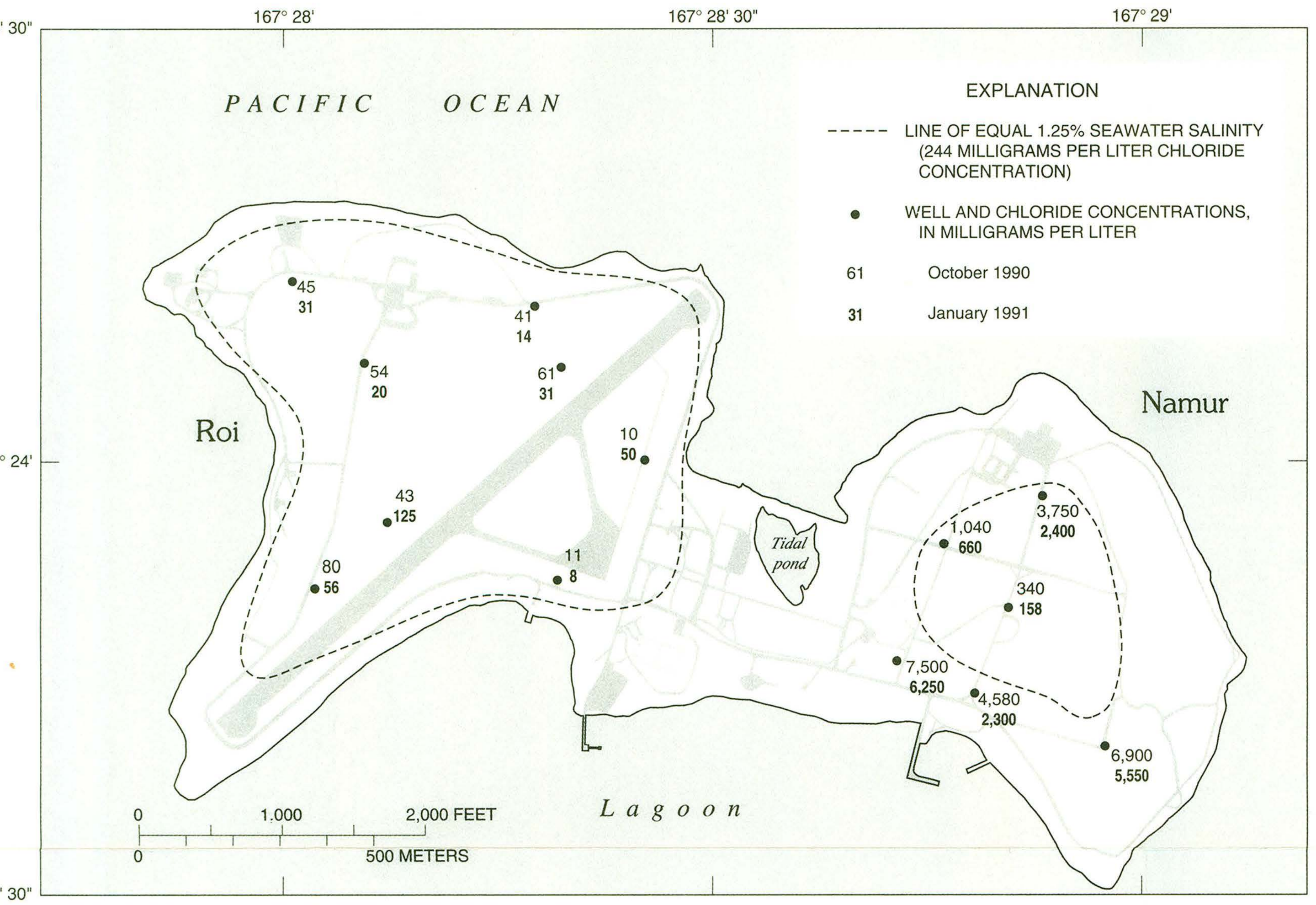

Figure 7. Chloride concentrations in shallow wells, October 1990 and January 1991. The extent of potable freshwater in January 1991 is approximated by the line of 244 milligrams per liter chloride concentration, and is based on non-pumping conditions.

AREAL EXTENT OF THE FRESHWATER LENS

The freshwater lens extends throughout the central area of Roi but is thin or absent in the central isthmus and on Namur, which is heavily vegetated.

The areal extent of the freshwater lens can be shown by a map of salinity (fig. 7) based on measurements from water samples pumped from shallow wells (most less than 10 feet below sea level) perforated at or near the water table. The contour line of 1.25-percent seawater salinity delineates the approximate extent of potable freshwater, which is defined in this report as water that has a salinity low enough to meet drinking-water standards (see next section). Although most of the sampled wells extend less than 10 ft below sea level, some part of the areal variation in salinity may be attributable to differences in the depths and perforated lengths of the wells.

Freshwater is most abundant in the central area of Roi where the aircraft runway is. The freshest ground water is in areas where recharge is inferred to be moderate to high. Wells outside the dashed line in figure 7 are unlikely to produce potable water.

Definition of potable freshwater.--Salinity in a freshwater lens is gradational, from an upper freshwater core through the underlying transition zone to saltwater. Alternate definitions of the freshwater lens could be selected that would:

(1) include only the lens core of potable freshwater in the lens;

(2) include the potable core and the freshwater-saltwater transition zone (because it contains a fractional component of freshwater); or

(3) include the potable core and the top half of the transition zone to the depth of 50-percent seawater salinity (because that depth corresponds with the Ghyben-Herzberg depth to a theoretical freshwater-saltwater interface) (see fig. 2A).

Although definitions 2 and 3 are appropriate for certain types of analyses, the core of potable freshwater is most relevant for the purposes of this report. Potable water is water that is suitable for drinking, and is defined here solely on the basis of salinity. Chloride concentration was used as a measure of salinity, and relative salinity is defined as mg/L chloride divided by 19,500 mg/L chloride (seawater chloride concentration), multiplied by 100. Therefore, 1.25-percent salinity is equivalent to 244 mg/L chloride concentration, just below the 250 mg/L maximum contaminant level (MCL) for drinking water recommended as a secondary standard by the USEPA (U.S. Environmental Protection Agency, 1989). Chloride concentration is used here as an index of salinity because it is relatively easy to measure and is an accurate indicator of the saltwater fraction in freshwater-saltwater mixtures. Secondary standards are not mandatory requirements, but instead establish limits for constituents that may affect the aesthetic qualities of drinking water (taste and odor, for example). Other naturally occurring constituents can also limit the suitability of water for drinking. For example, dissolution of calcium carbonate sediments at Roi-Namur causes high concentrations of dissolved solids in even the freshest ground water. Therefore, the secondary standard maximum contaminant level for total dissolved solids (500 mg/L) might be exceeded even though that for chloride is not.

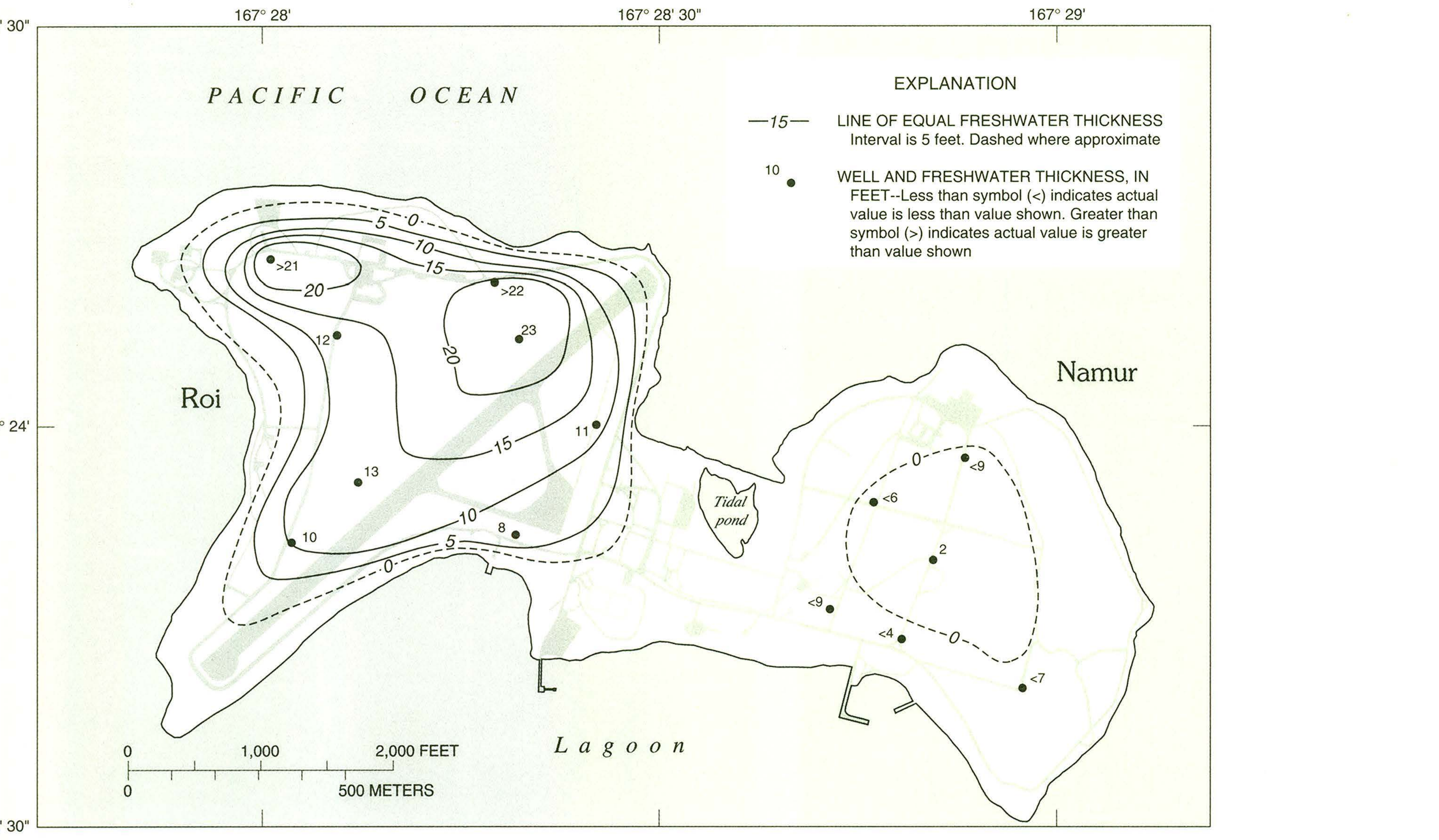

Figure 8. Thickness of the freshwater lens for non-pumping conditions, Roi-Namur Island, January 1991.

THICKNESS OF THE FRESHWATER LENS—MAP VIEW

The freshwater lens attains a maximum thickness of 23 ft, and its main body lies beneath the central area of Roi where recharge is high. The freshwater thickness map can be used to estimate the volume of potable water underlying the islands.

Although the freshwater lens occupies a three-dimensional volume, its size and shape can be represented in two dimensions by a map showing lines of equal lens thickness (fig. 8). As indicated by the lines of equal thickness, the freshwater lens is roughly circular, similar to the shape of the island. The thickest part of the lens coincides with grassy areas where recharge is concentrated. Lens thickness is not known in the isthmus because of a lack of wells. The lens is thin on Namur because of a high evapotranspiration rate from the thick vegetation.

A small amount of seasonal freshwater lens shrinkage and expansion was detected during the field study. Data for October 1990 and January 1991 were similar. However, the data indicate thickening of the lens from October 1990 to January 1991. Maximum lens thickness was only 20 ft in October 1990 (during the wet season), in contrast with maximum thicknesses of 23 ft in January 1991 (after the wet season).

The volume of potable water in the aquifer can be estimated from the map of freshwater thickness by multiplying an estimate of the total volume of the aquifer containing the freshwater lens by the estimated porosity of the aquifer (0.3). The estimate of potable water underlying Roi is 30.2 x 10^6 ft^3 (226 Mgal) and underlying Namur is 0.56 x 10^6 ft^3 (4.2 Mgal). About 10.0 x 10^6 ft^3 (75 Mgal) of water with a concentration less than 20-percent seawater salinity is available on Namur for nonpotable uses.

The central area of Roi between wells R1 and R10 holds the greatest potential for developing additional potable ground water with new wells as indicated by the maps of the thickness and areal extent of freshwater.

Preparation of the freshwater-thickness map.--Water samples were collected from monitoring and withdrawal wells during a 1-week period in January 1991, when no water was being withdrawn from the lens well. This was the same water-sampling survey used to map the areal extent of freshwater. The chloride concentration of each water sample was measured and relative salinity values were determined. The thickness of potable freshwater was estimated for each of the sampled wells shown. The thickness estimates include water above and below sea level, from the water table to the estimated depth of 1.25-percent seawater salinity. The estimates vary in accuracy from well to well. At multi-depth monitoring wells, depth profiles of salinity were drawn, and the depth of 1.25-percent seawater salinity was estimated by interpolation between the two wells that bracketed it vertically (for a fuller explanation, see the next section, "Thickness of the freshwater lens and transition zone"). At two-well sites, it was usually possible to determine only whether freshwater was present or absent; if the water was fresh, then freshwater thickness was assumed to exceed the depth of the well. The thickness estimates were plotted on the map at corresponding well locations, and contour lines were hand-drawn by visual interpolation.

THICKNESS OF THE FRESHWATER LENS AND TRANSITION ZONE—SECTIONAL VIEW

The freshwater lens is thickest in the center of Roi, and is underlain by an asymmetric freshwater-saltwater transition zone that is several times thicker than the freshwater lens itself.

Sections of ground-water salinity (fig. 9) were drawn using data from the water-sampling survey of January 1991. Locations of the sections (fig. 6) were chosen to illustrate conditions in the thickest parts of the freshwater lens. Salinity is expressed as relative salinity (a percentage of seawater salinity). Lines of equal salinity define the shape and thickness of the freshwater lens and underlying transition zone. The 1.25-percent line encloses the potable freshwater core of the lens (1.25 percent is approximately equivalent to a chloride concentration of 250 mg/L). The shape of the freshwater lens is almost symmetric across the island axis in sections *A-A'* and *B-B'* but slightly thicker at R10. The reason for this is unknown. Section *C-C'* on Namur shows only a small freshwater lens because of low recharge caused by thick vegetation and high evapotranspiration rates.

The transition zone between freshwater and saltwater is defined for the purposes of this discussion as excluding potable freshwater (less than 1.25-percent seawater salinity) and water with the corresponding salinity (more than 98.75 percent) at the saltwater end of the salinity distribution. Rather than approximating a sharp interface, the transition zone is thicker than the freshwater lens-by a factor of two or more in most places. None of the monitoring wells penetrated deep enough to encounter 98.75 percent salinity, but the shape of the transition zone is readily apparent in the sections in figure 9. The largest ratios of transition-zone thickness to lens thickness are at oceanward sites, indicating that aquifer hydraulic properties or flow-system dynamics favor greater mixing there. Tide-induced ground-water fluctuations are generally greater at the oceanward side of the aquifer, perhaps because of a larger proportion of highly permeable, coarse sediments deposited in high-energy near-reef and beach-face environments.

The transition zone beneath Roi is asymmetric in most places, with a thicker lower half (between the 50- and 90-percent lines) indicating a more gradual change in salinity with depth, and a thinner upper half (between the 10- and 50-percent lines). This is an expected result of more active flushing of the upper part of the transition zone by lateral freshwater flow (Bear and Todd, 1960).

Preparation of the sections.--Three lines of section were oriented across Roi and Namur. The lines on Roi are roughly perpendicular to the airfield lens well, and are nearly perpendicular to lines showing equal freshwater thickness and water-table altitude. The lines pass through most sampled wells, although some wells are projected onto the lines over short distances. Relative salinity was computed for each sample from its measured chloride concentration, assuming that waters are a mixture of saltwater and freshwater end members (Vacher, 1974). Chloride concentrations of 19,500 mg/L and 0 mg/L were selected as end-member values to bracket the highest chloride concentration measured in seawater during the study (19,450 mg/L) and the lowest concentration in rainwater (1 mg/L). This simple mixing model is not strictly accurate for ground water with very low salinity, in which some chloride originates from dry deposition of sea-salt aerosols and evaporative concentration of salt from rainfall, rather than from mixing with sea water.

The values of relative salinity were plotted on the sections at depths corresponding to the midpoint of each well's perforated interval. At multi-depth monitoring wells, depths of selected salinities (1.25-, 10-, 50-, and 90-percent) were estimated by an interpolation method and plotted. The interpolation method entails plotting salinity as a function of depth on normal probability graph paper, with depth on the linear axis and salinity on the probability axis. The method is consistent with the theoretical profile of salinity in the transition zone and approximates the characteristic S-shape of the cumulative normal probability distribution. Plotting on probability paper transforms the S-shape to a straight line, allowing the depth of a given salinity to be estimated by straight-line interpolation (Vacher, 1974).

Lines of equal salinity were hand-drawn for the selected salinities (which are numerically symmetric about the 50-percent concentration). At some wells, the positions of the deeper salinity lines were estimated by extrapolating beyond the maximum well depth to provide a more complete picture, but the positions of these lines are highly speculative.

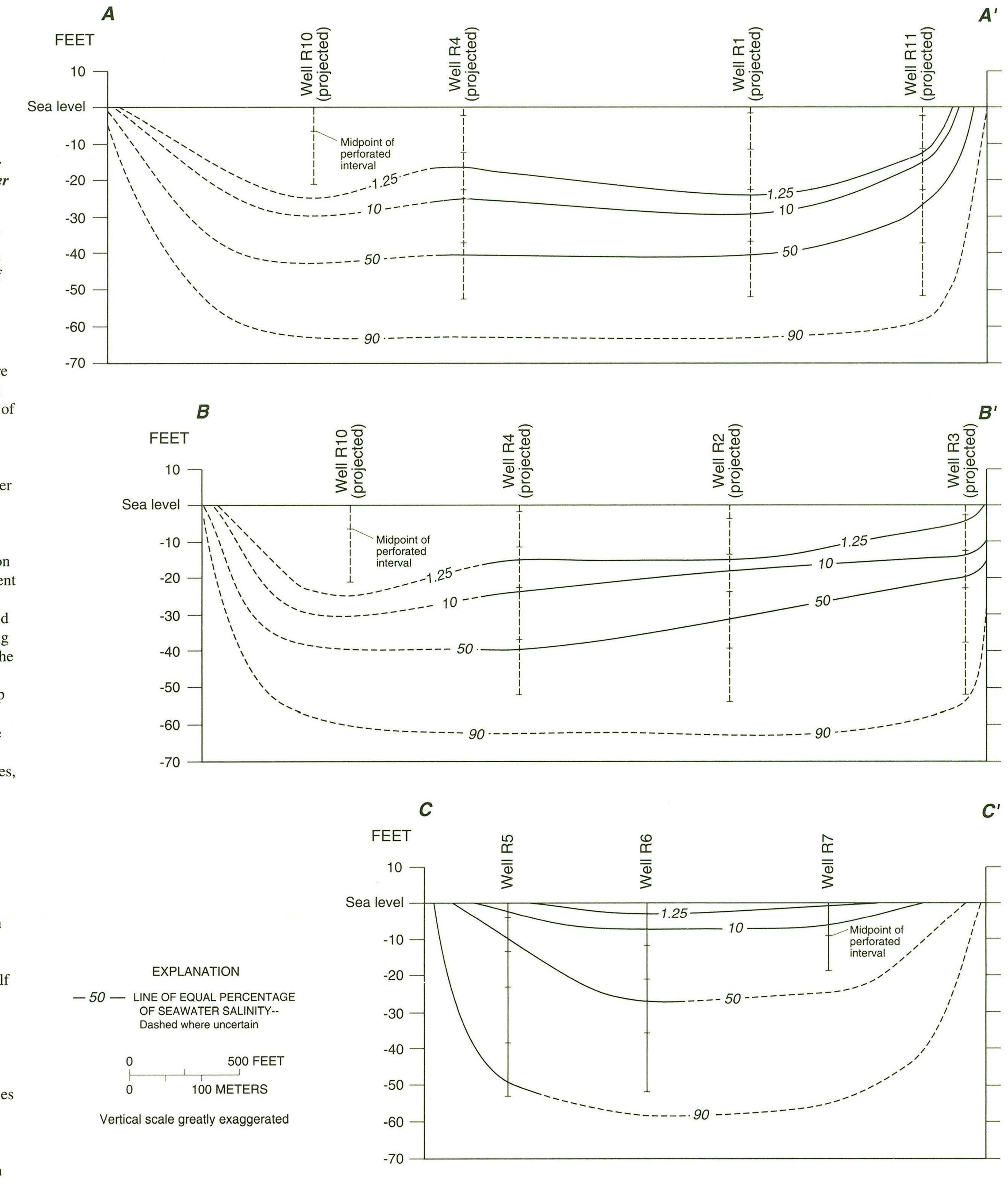

Figure 9. Thickness of the freshwater lens (to depth of 1.25-percent line) and transition zone (between 1.25- and 90-percent lines), Roi-Namur Island, January, 1991. Lines of sections are shown in figure 6.

GROUND-WATER RESOURCES AND CONTAMINATION AT ROI-NAMUR ISLAND, KWAJALEIN ATOLL, REPUBLIC OF THE MARSHALL ISLANDS, 1990-91

by

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